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TECHNICAL NOTE

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STATIC THRUST OF AN ANNULAR NOZZLE WITH A CONCAVE CENTRAL BASE

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STATIC THRUST OF AN ANNULAR NOZZLE WITH A CONCAVE CENTRAL BASE

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SUMMARY

A static test of an annular nozzle with a concave central base, producing a jet in which tangents to the jet streamlines at the exit converged toward a region on the axis of symmetry downstream of the exit, has indicated good thrust performance. A value of nozzle-flow coefficient only slightly less than unity indicates the internal loss to be small. Pressures on the concave central base are relatively large and positive, and a predictable portion of the total thrust of the jet is exerted on the central base.

INTRODUCTION

In work on jet exits, two facets of design and operation which have received considerable attention and which have a major effect on overall performance are base and afterbody pressures and design for efficient operation over a wide range of pressure ratio. For many jet-engine configurations the primary exit area is between 20 and 30 percent of the engine maximum cross-sectional area. In order to obtain a reasonably well streamlined nacelle external contour for an engine with a convergent nozzle, either an undesirably long tailpipe must be used to avoid a steeply boattailed afterbody or, with a shorter tailpipe, an annular base between the tailpipe exit and the nacelle external fairing must be accepted. The use of either a steeply boattailed afterbody or an annular base entails a drag penalty through the action of low pressures on these regions during flight. (See ref. 1.)

In supersonic flight, jet engines generally operate at sufficiently high values of pressure ratio to require use of a convergent-divergent nozzle. Because the jet exit area for the convergent-divergent nozzle is larger than a simple convergent exit for equal mass flow, the design of the afterbody boattail and annular base presents a less difficult problem. Another problem arises, however, for the convergent-divergent nozzle with regard to off-design operation. An internal-expansion convergent-divergent nozzle, including ejector types, operates with

high efficiency at its design pressure ratio but may suffer a severe loss of thrust at values of pressure ratio not near the design value (ref. 2). The external-expansion convergent-divergent nozzle, however, consisting of an annular exit with either a conical or an isentropic central plug will operate efficiently over a wide range of pressure ratio (ref. 3).

In an earlier study of axial flow past a cylindrical body with a blunt base, a vortex-ring type of flow was found to exist in the region downstream of the base. Evidence of such a flow is illustrated in figure 1, which is a photograph of a dye trace on a plate mounted at the base of the cylindrical body coincident with the axial plane of symmetry. The direction of this enclosed flow was downstream at its outer edges and upstream along the axis. Further evidence of vortex-ring flow and pressure recovery on the base was obtained from the data of reference 4, which presents the radial distribution of pressure on the base of a cylindrical body in the presence of several jets clustered symmetrically about the body axis. Although the jet axes were parallel to the body axis, at high pressure ratios the boundaries of the expanding jets impinged on the body axis downstream of the exits and apparently set up a circulatory flow in the region bounded by the clustered jets. At high values of pressure ratio, the pressure at the center of the base was increased appreciably.

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The foregoing considerations have led to an attempt to simplify the plug-type nozzle by eliminating all fixed boundaries of the jet downstream of the annular sonic exit. The resultant configuration is an annular nozzle with a concave central base and is shown in the sketch presented as figure 2. With this type of nozzle, it is intended that the jet streamlines as they issue from the annular exit be convergent toward a region on or near the axis of symmetry downstream of the exit, and that a vortex-ring type of flow be established in the cone-shaped region bounded by the inner surface of the convergent jet and the concave base as indicated in figure 2. It was believed that the force required to redirect the jet streamlines to an axial direction would be sensed as a pressure rise in the vortex-ring flow and exerted as thrust on the concave central base. The concave shape for the central base was selected because it was believed that this shape would be conducive to establishing and maintaining a vortex-ring type of flow in the base region.

The purpose of the present work was to make an exploratory investigation of the static performance of an annular nozzle with a concave central base. The main points of inquiry were the following: the distribution and general level of pressure on the central base, nozzle-flow coefficient, the variation of base thrust with jet pressure ratio, and the variation of overall thrust with jet pressure ratio. The

test was conducted in the jet-exit test stand of the Langley 16-foot transonic tunnel.

SYMBOLS

A_p — primary exit area (determined by truncated-cone surface having 60° half-angle, fig. 3), sq ft

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C_d — flow coefficient, w/w_i

C_F — thrust coefficient, $F/A_p p_\infty$

$C_{F,b}$ — base thrust coefficient, $F_b/A_p p_\infty$

$C_{F_{i,c}}$ — ideal jet thrust coefficient for convergent nozzle, $F_{i,c}/A_p p_\infty$

F — measured thrust, lb

F_b — base thrust, $2\pi \int_0^R (p_b - p_\infty) r \, dr$, lb

$F_{i,c}$ — ideal jet thrust for convergent nozzle,
$$\frac{w}{g}\sqrt{\frac{2\gamma}{\gamma + 1} gRT_{t,j}} + A_p(p_j - p_\infty), \text{ lb}$$

g — gravitational acceleration, ft/sec^2

M — Mach number

p — static pressure, lb/sq ft

p_t — total pressure, lb/sq ft

$p_{t,j}/p_\infty$ — ratio of primary jet total pressure to ambient static pressure

R — gas constant (69.89 for 90 percent H_2O_2 products at $1,364^{\circ}$ F), ft/$^{\circ}$R; or base radius, in.

r — distance from base center to pressure orifice, in.

T_t — stagnation temperature, $^{\circ}$R

w measured weight flow, lb/sec

w_i ideal weight flow for sonic exit,

$$p_{t,j}A_p\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\sqrt{\frac{\gamma g}{RT_{t,j}}}, \text{ lb/sec}$$

x distance from nozzle exit, positive forward, in.

α angle of attack, deg L

γ ratio of specific heats (1.266 for 90 percent H_2O_2 products at 1,364° F) 851

θ discharge angle (see fig. 2), acute angle between axis of symmetry and tangent to jet streamline at exit, deg

ϕ meridian angle, positive clockwise looking forward from point downstream of nozzle exit, deg

Subscripts:

b base

j jet

t total, stagnation

∞ ambient (atmospheric)

APPARATUS AND METHODS

The present investigation was conducted at the jet-exit test stand of the Langley 16-foot transonic tunnel. A hydrogen peroxide turbojet-engine simulator of the type described in reference 5 was used. The configuration studied consisted of a convergent nozzle with a concave central base which formed an annular exit. A sketch of the configuration is presented in figure 3, and a photograph is presented in figure 4.

The instrumentation included an external one-component strain-gage thrust balance, a total-pressure probe and a stagnation-temperature probe located in the tailpipe, static-pressure orifices on the nozzle lip and on the concave central base, and an impeller-type electronic flowmeter. The pressures were measured with electrical pressure

tranducers with outputs transmitted through carrier amplifiers to oscillographs. The thrust-balance and flowmeter outputs were also recorded on the oscillographs. The jet stagnation temperature was measured on a pen-trace self-balancing potentiometer. Machine computation was used to convert the pressures and forces to coefficient form. Data are also presented for measurements of thrust, jet total pressure, and weight flows which were recorded with the use of an automatic digitizer system.

The estimated accuracy of the pressure measurements is ±2 percent. Thrust measurements are estimated to be accurate within ±4 pounds of thrust, and measured weight flow is estimated to be accurate within ±0.02 pound per second.

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RESULTS AND DISCUSSION

The results of the measurements of static thrust, base pressures, and weight flow for the annular nozzle with a concave central base are presented in figures 5 to 10. The pressures on the external surface of the nozzle outer lip varied so little from the ambient atmospheric pressure that they had no measurable effect on thrust and are therefore not presented.

Weight Flow and Flow Coefficient

The variation of measured weight flow with jet total-pressure ratio is presented in figure 5. The accuracy of these measurements suffered somewhat because the metering equipment had been sized for use with larger nozzles and this fact is reflected in the scatter of the data. Also shown is the variation with jet total-pressure ratio of ideal weight flow for this nozzle with no losses. Nozzle-flow coefficient, the ratio of measured to ideal weight flow, is presented in figure 6. The values obtained are approximately the same as for conventional nozzles that have small internal loss.

Base Thrust

Pressure distributions on the concave central base are presented in figure 7, as radial variation of pressure coefficient, for several values of jet total-pressure ratio. Although the pressure distribution on the base is relatively uniform for a given value of pressure ratio, the pressures at the center of the base $(r/R = 0)$ and at the outer edge $(r/R = 1)$ where the base is "dished" are consistently greater than the average. The higher pressure in these regions is

interpreted as evidence of a vortex-ring type of flow contained between the converging annular jet and the concave base. (See fig. 2.) The circulating flow directed upstream along the center line contains a stagnation point at the center of the base, indicated by the higher pressure, and, with radial flow from the center, another stagnation region near the outer edge of the base where the flow is turned downstream by the curved edge of the base and by the barrier action of the annular jet.

The consistent increase in average pressure on the base as the jet total-pressure ratio is increased (fig. 7) indicates that a large portion of the total thrust is exerted on the base. The pressure distributions of figure 7 were integrated over the base area and the values of force thus obtained were reduced to base thrust coefficient. The variation of base thrust coefficient with jet total-pressure ratio is shown by the lowest curve in figure 8.

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As mentioned previously, the direction of the flow from the annular nozzle is deliberately inclined to the thrust axis at an angle θ, designated the discharge angle. The direct thrust sensed by the annular nozzle, then, is the $\cos\theta$ component of the jet thrust. Inasmuch as the jet streamlines converge toward the axis of symmetry downstream of the nozzle and base and are redirected in an axial direction, the full thrust of the jet must be sensed by the complete system. This reasoning implies that thrust exerted on the base is the $(1 - \cos\theta)$ component of the total jet thrust; that is,

$$F_b = (1 - \cos\theta)F_j$$

Ratio of Base Thrust to Total Thrust

The variation of base thrust coefficient with total-thrust coefficient is shown in figure 9. The variation is linear within the range of pressure ratio investigated in this test, and the slope of this line (0.187) represents the fraction of the total thrust exerted on the base. This value should also be equal to $(1 - \cos\theta)$. The lips of the annular nozzle were designed and made with an inclination of 30° to the axis of symmetry, as indicated in figure 3. After assembly, however, it was found that a line normal to a straight edge across the lip extremities (in a plane containing the axis of symmetry) was inclined 38° to the axis of symmetry, due to axial mislocation of the central base. The effective discharge angle computed from the relation $(1 - \cos\theta) = 0.187$ yields a value for θ of 35.6° which, within the accuracy of these measurements, is regarded as a qualitative verification of the relation

$$F_b = (1 - \cos\theta)F_j$$

Total Thrust

The variation of total-thrust coefficient with jet total-pressure ratio is presented in figure 8, which shows a comparison of measured with ideal values. The ratio of measured to ideal thrust (in coefficient form) as a function of jet total-pressure ratio is given in figure 10. In an effort to account for the relatively low values of thrust coefficient at the lower values of pressure ratio, an estimate was made of the internal skin-friction loss. This calculation indicated the internal loss of thrust to be less than one-half percent of the ideal. A low internal loss is also indicated by the relatively high values of flow coefficient obtained (about 0.98, fig. 6). The low values of thrust-coefficient ratio shown in figure 10 at the lower values of pressure ratio, therefore, are not attributed to internal loss. On the other hand, the static-thrust performance of this nozzle even at the lower values of pressure ratio is about the same as that of many conventional convergent nozzles; in addition, an encouraging aspect of the results shown in figure 10 is that the ratio of measured to ideal thrust increases with increasing jet total-pressure ratio within the range covered in this investigation. Conventional convergent nozzles in general show an opposite trend. This increasing ratio of measured to ideal thrust with increasing pressure ratio for the annular nozzle with a concave central base is taken to indicate at least partial performance as a plug-type convergent-divergent nozzle; the pressurized circulating flow contained between the concave base and the converging annular jet is assumed to act as a "plug" insofar as the jet flow is concerned.

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Although the results obtained in these measurements of static thrust are of considerable interest, the usefulness of an annular nozzle with a concave central base in application to the propulsive system of a jet aircraft will be dependent upon its performance in an airstream with external axial flow surrounding the afterbody and convergent annular jet. In the vicinity of the convergent annular jet, reduced pressure may be generated in the external flow which may be transmitted radially (or along Mach lines) through the jet to the vortex-ring flow and thence to the base. In this case the nozzle would suffer severe loss of thrust. An equal possibility, however, is that pressure recovery in the converging external flow may be transmitted through the jet to the jet-stagnation region and thence through the vortex-ring flow to the base to be sensed as increased thrust.

One possible application for this nozzle might be as a control nozzle for vehicles which employ reaction controls. The annular nozzle with shallow concave or flat central base is amenable to incorporation in a thin surface. Effective operation can be obtained at high values of jet total-pressure ratio without an extended bell-shaped nozzle as is normally required.

CONCLUDING REMARKS

A static test of an annular nozzle with a concave central base, producing a jet in which tangents to the jet streamlines at the exit converged toward a region on the axis of symmetry downstream of the exit, has indicated good thrust performance. A value of nozzle-flow coefficient only slightly less than unity indicates the internal loss to be small. Pressures on the concave central base are relatively large and positive, and a predictable portion of the total thrust of the jet is exerted on the central base.

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National Aeronautics and Space Administration,
Langley Field, Va., April 6, 1960.

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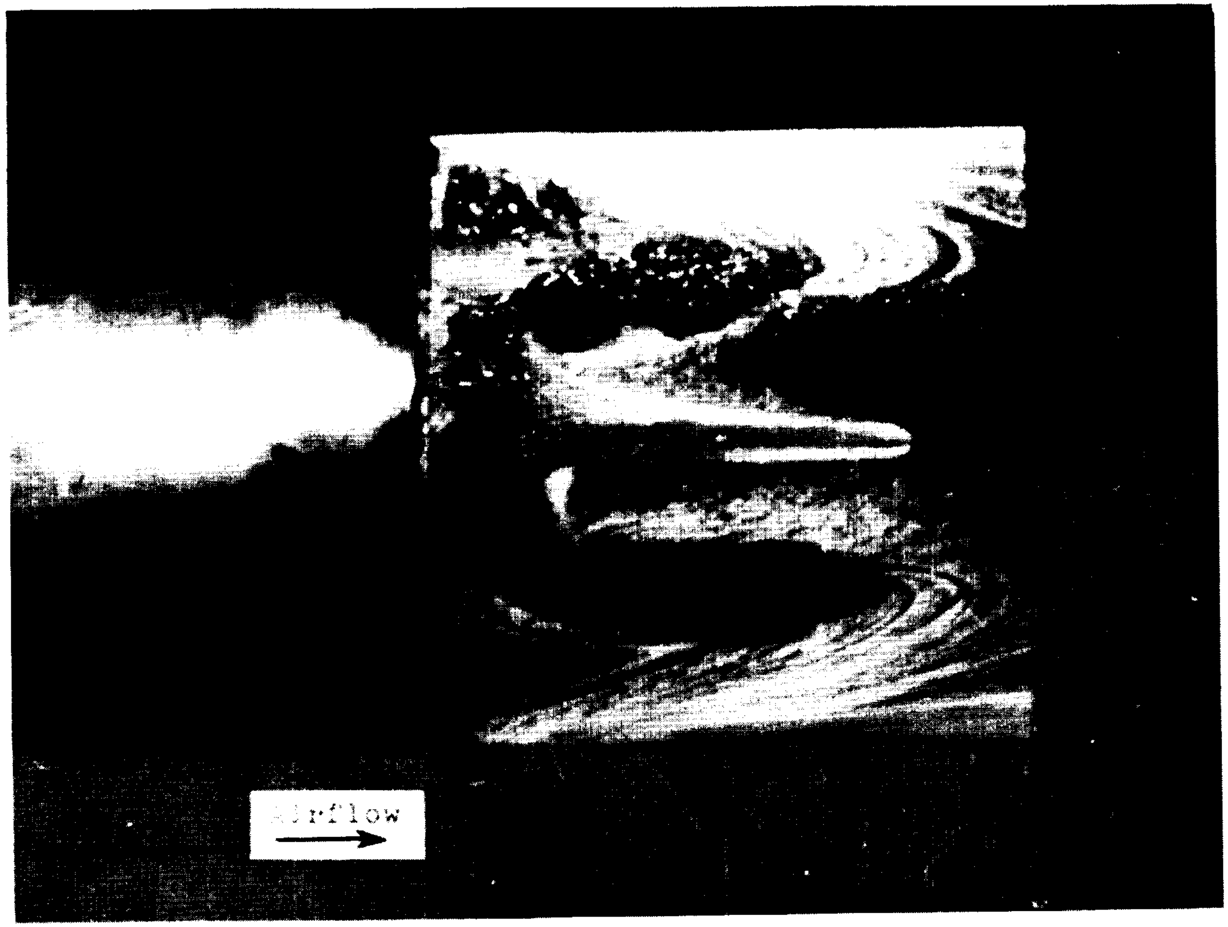

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Figure 1.- Dye trace of vortex-ring type flow at base of body of revolution in axial stream. $\alpha = 0^{\circ}$; $M = 0.90$.

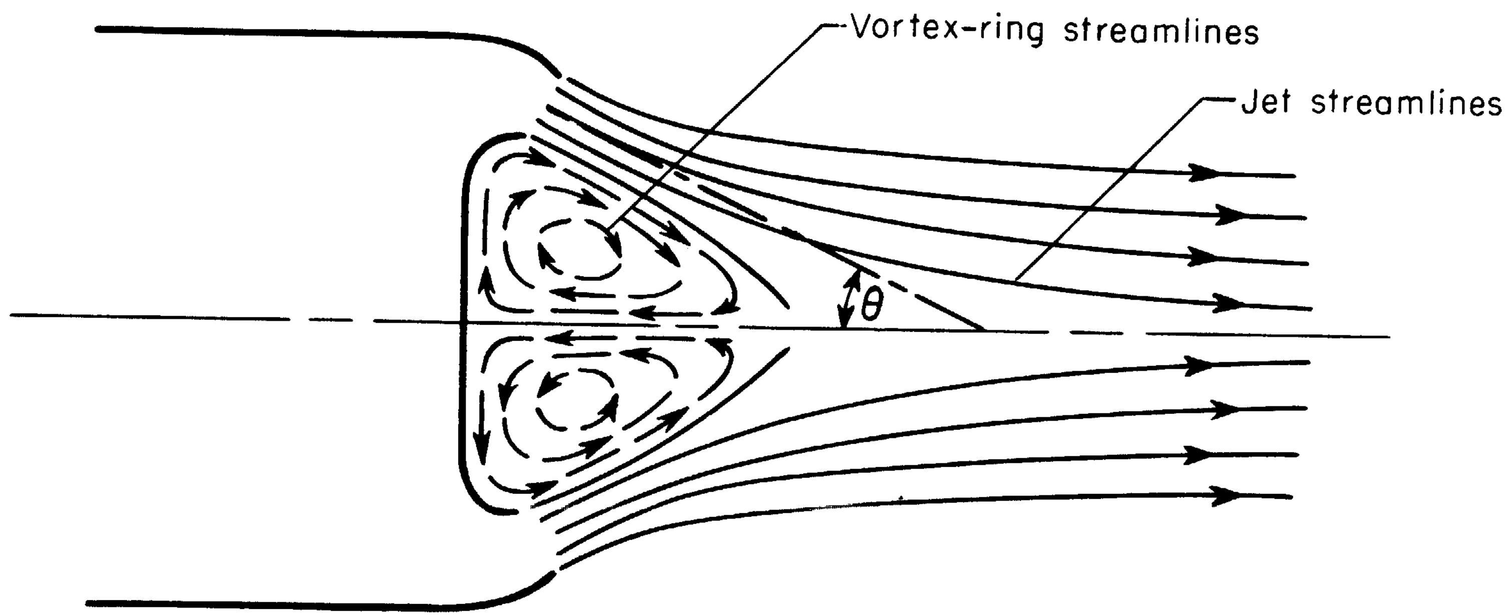
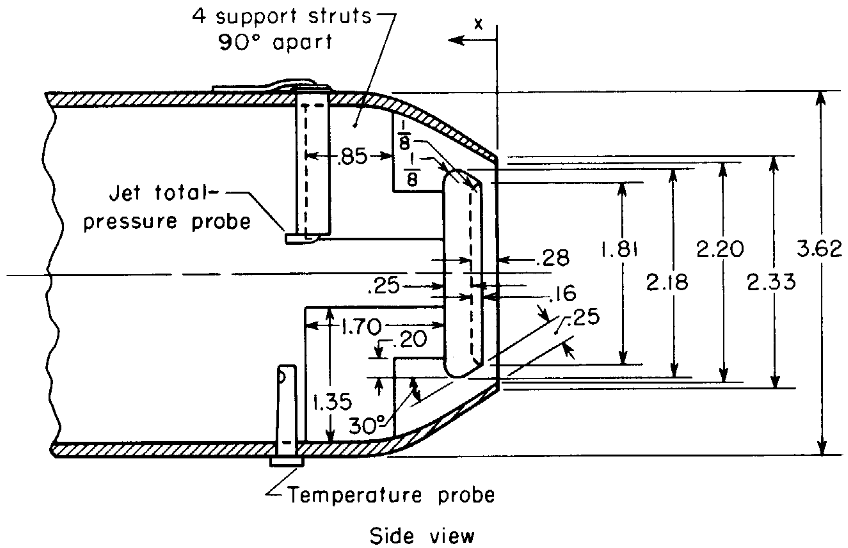
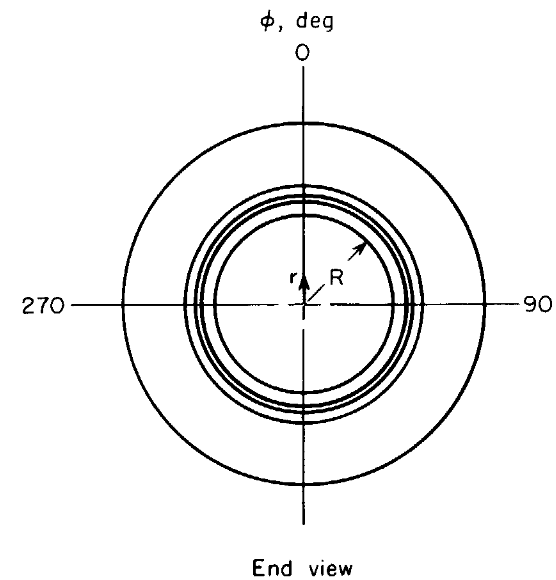
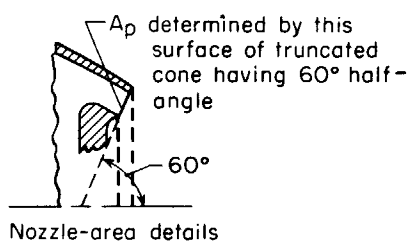


Figure 2.- Schematic longitudinal section of annular nozzle with concave central base.







Pressure-Orifice Locations				
Annular nozzle		Concave base		
Row	x	Row	r	r/R
ϕ = 90° and 270°	0.05	ϕ = 0°	0.00	0.00
	.65		.22	.24
			.44	.49
			.66	.73
			.88	.98

Figure 3.- Sketch of model annular nozzle with concave central base. All dimensions in inches.

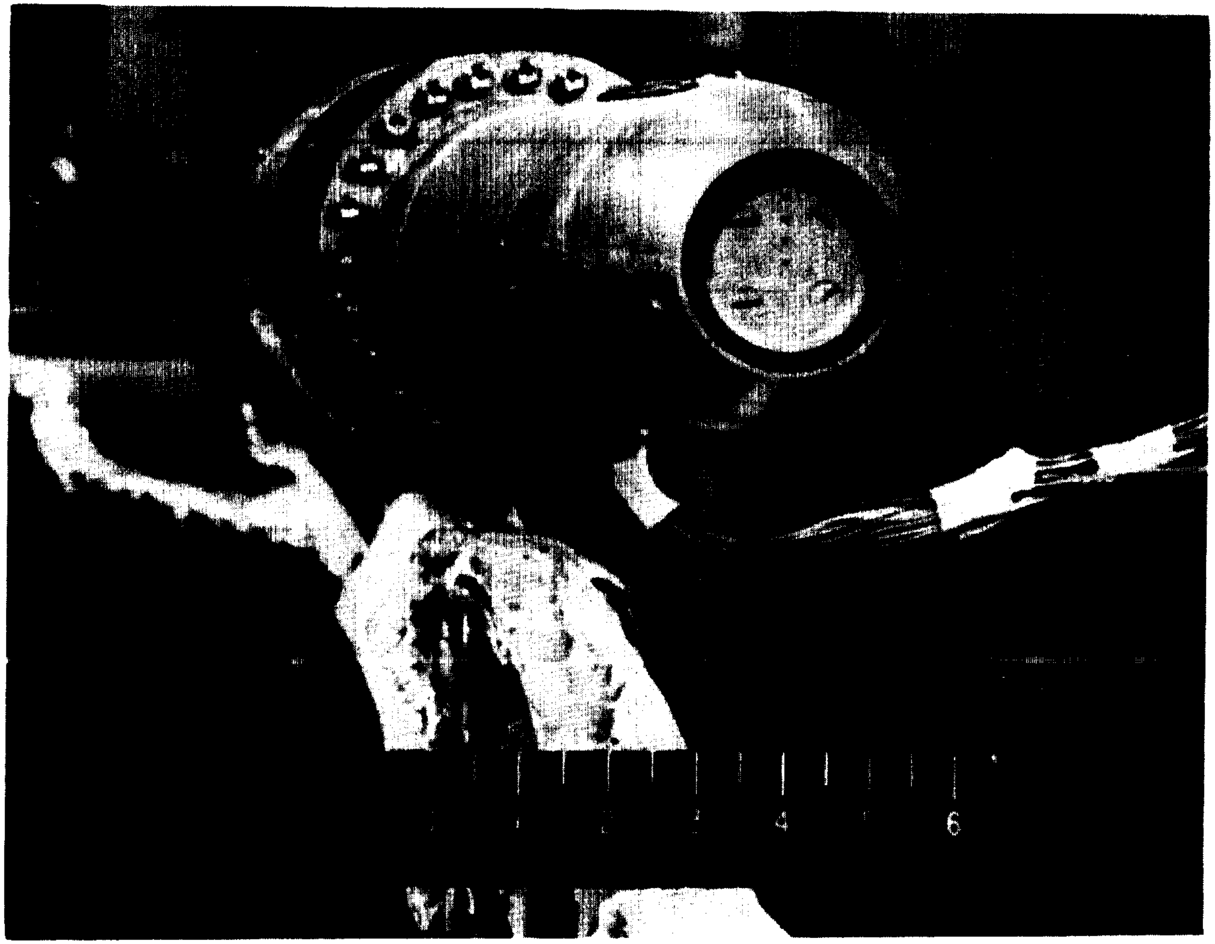


Figure 4.- Photograph of model.   L-59-4929

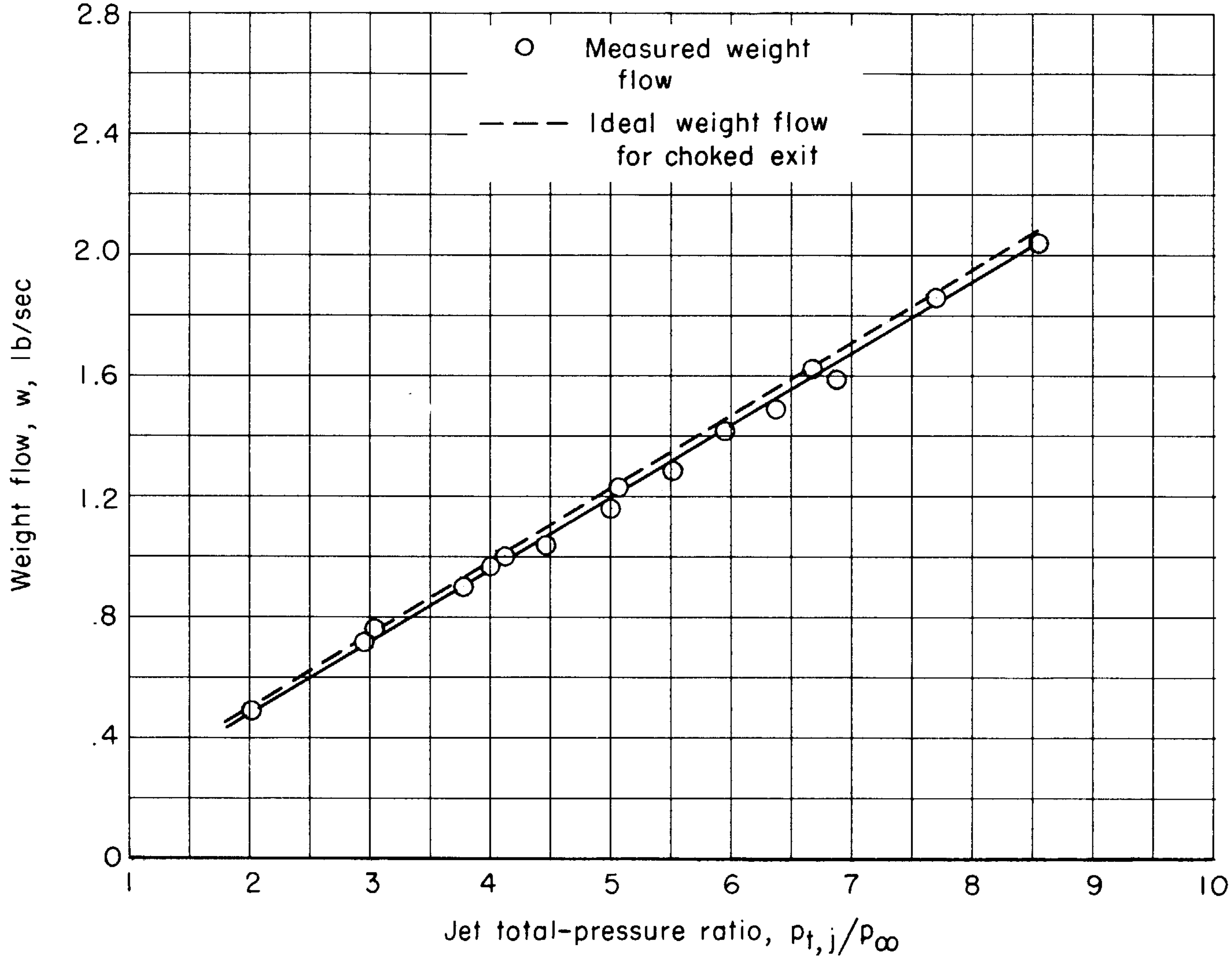


Figure 5.- Variation of weight flow with jet total-pressure ratio.

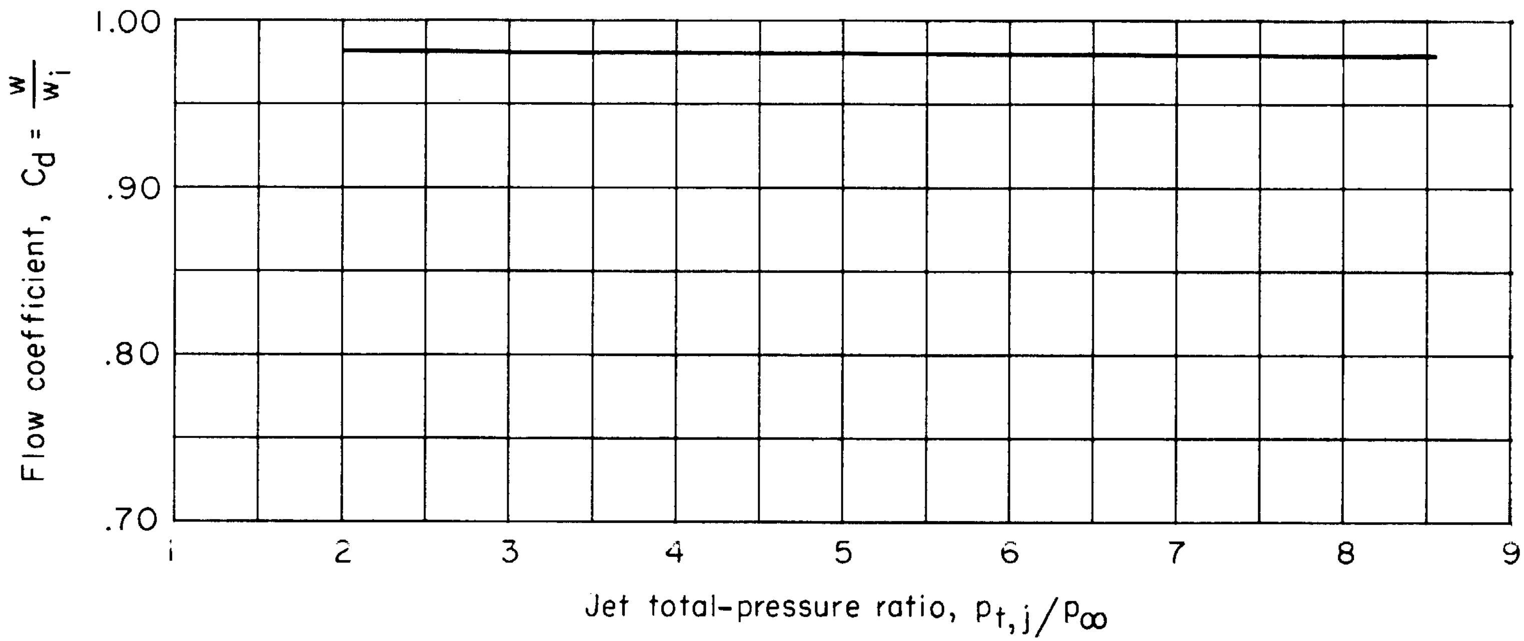


Figure 6.- Variation of flow coefficient with jet total-pressure ratio.

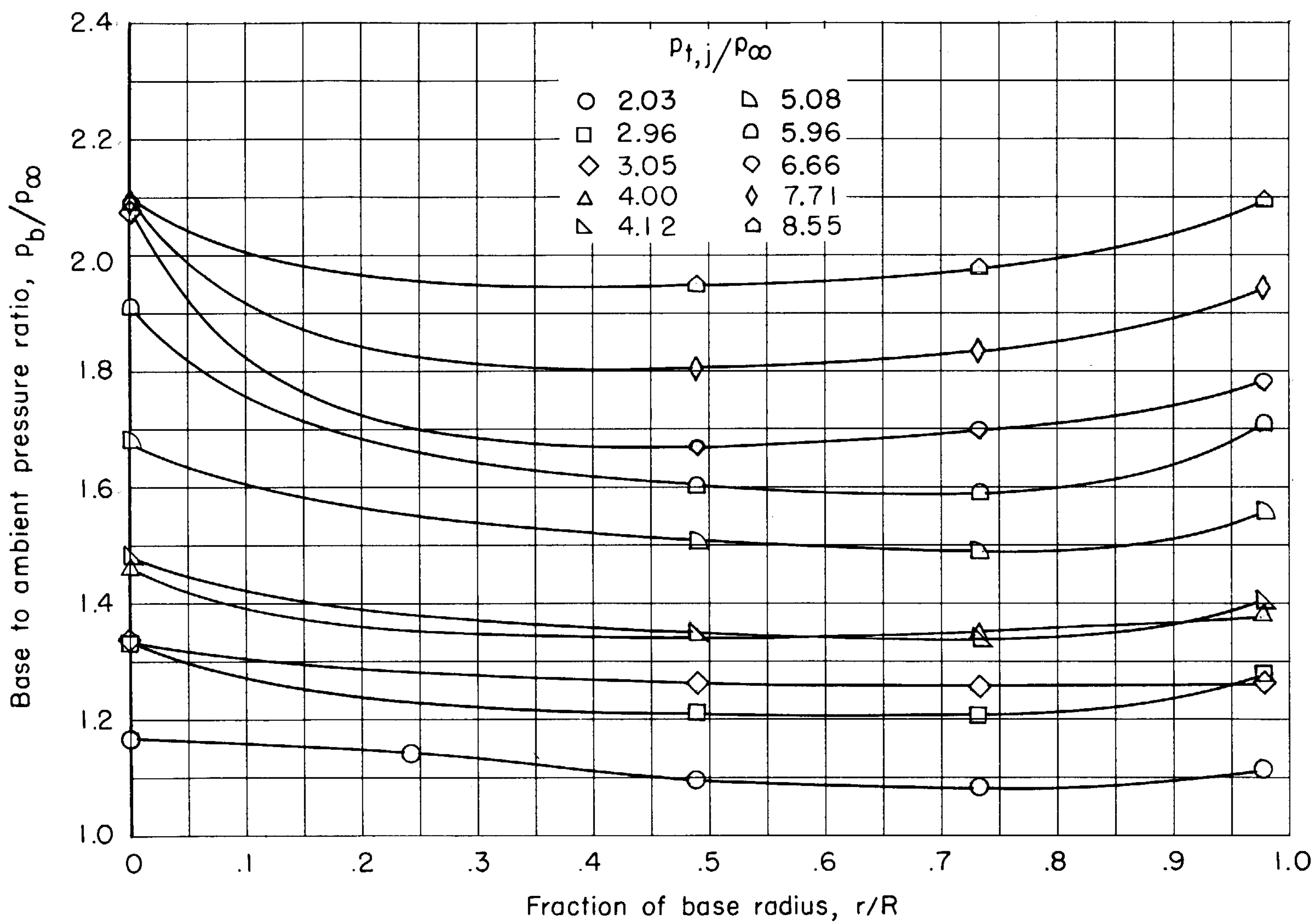


Figure 7.- Pressure distributions on concave central base for various jet total-pressure ratios.

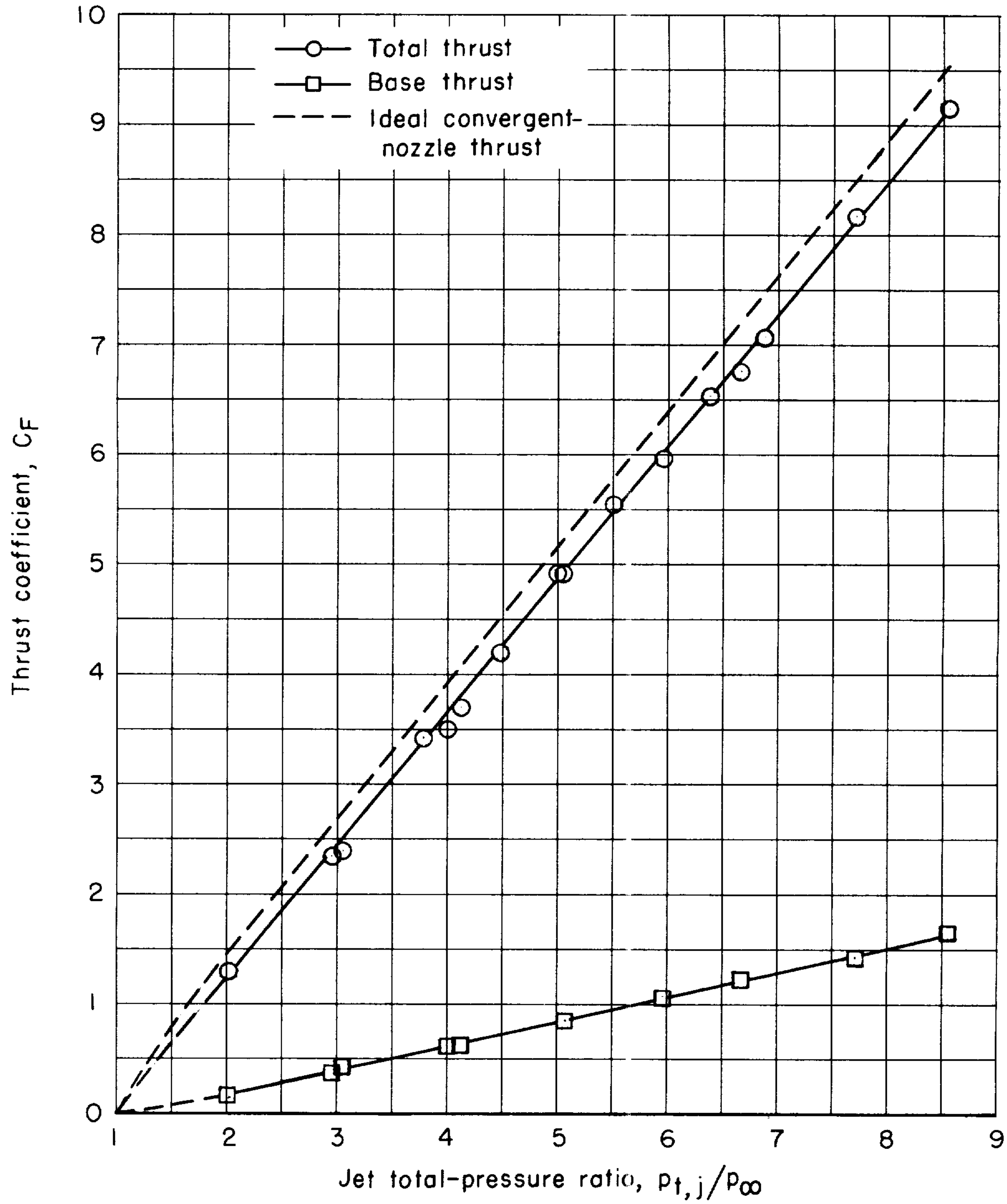


Figure 8.- Variation of thrust coefficient with jet total-pressure ratio.

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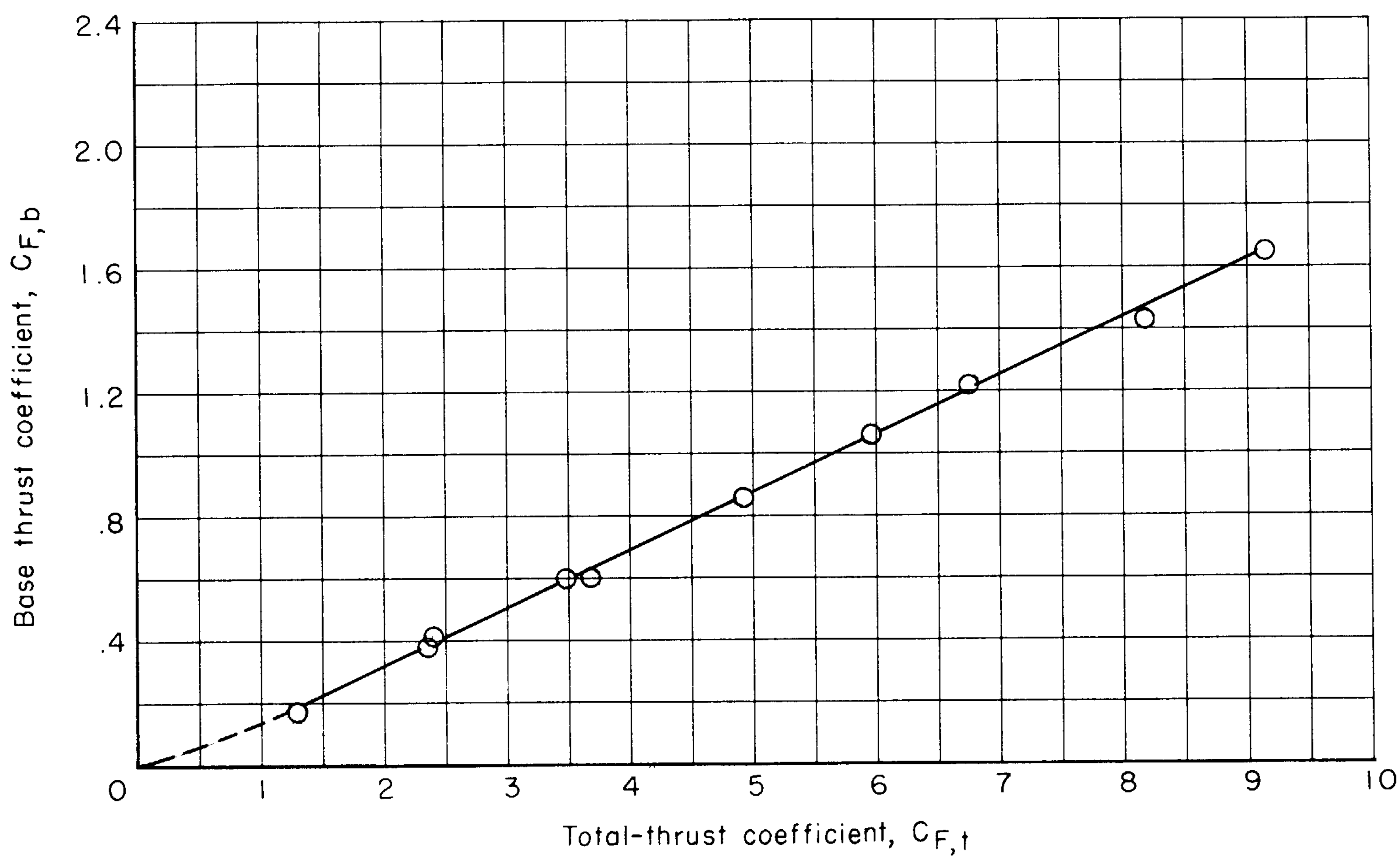

Figure 9.- Variation of base thrust coefficient with total-thrust coefficient.

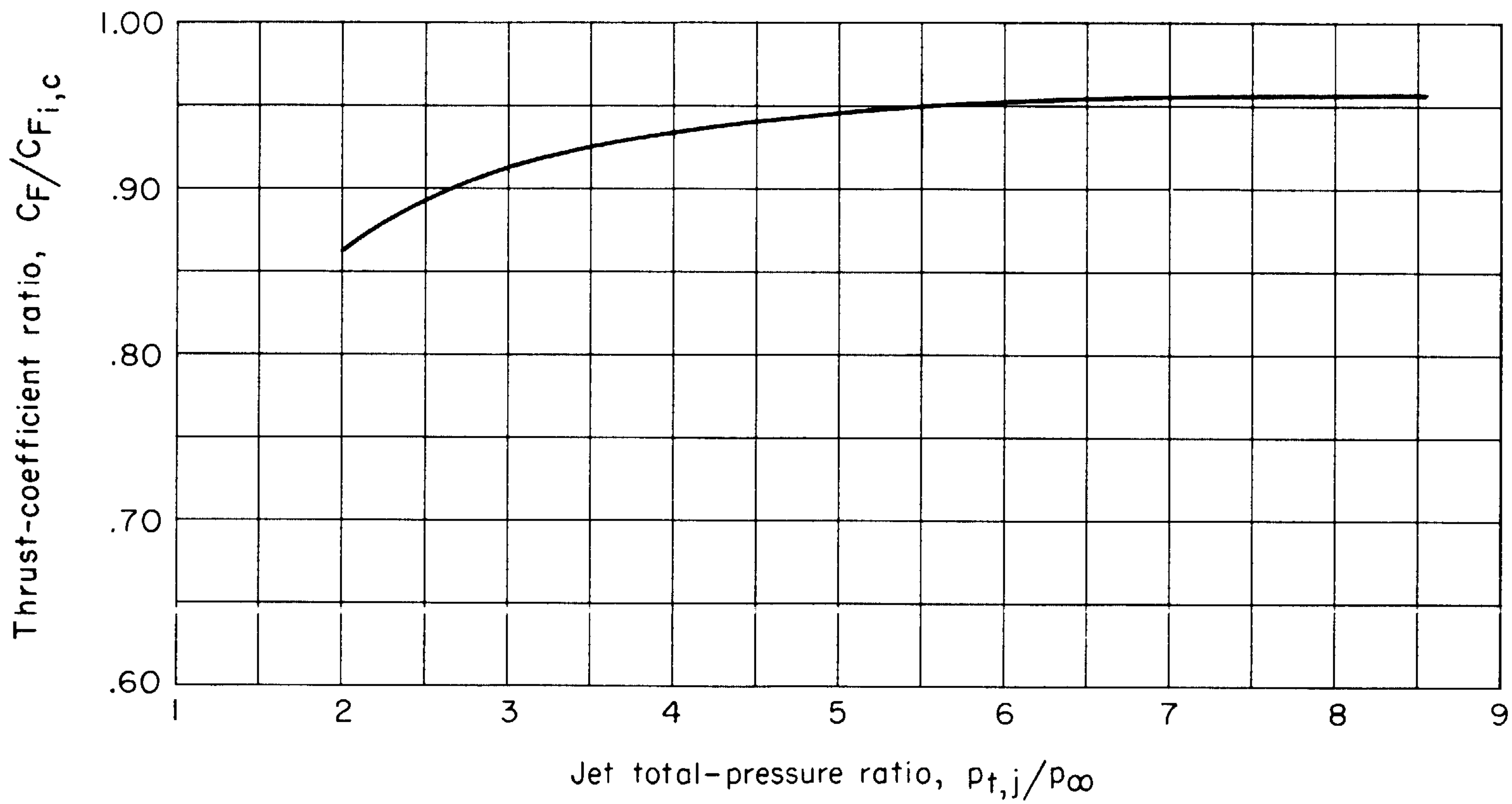

Figure 10.- Variation of thrust-coefficient ratio with jet total-pressure ratio.

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